

A&A manuscript no.
(will be inserted by hand later)

Your thesaurus codes are:
08(08.06.1, 08.16.5, 08.09.2 EX Lup)

ASTRONOMY
AND
ASTROPHYSICS
1.2.2008

The outburst of the T Tauri star EX Lupi in 1994

Thomas Lehmann^{1,2}, Bo Reipurth¹, and Wolfgang Brandner^{1,3}

¹ European Southern Observatory, Casilla 19001, Santiago 19, Chile

² Astrophysikalisches Institut und Universitäts-Sternwarte Jena, Schillergäßchen 2, D-07740 Jena, Germany

³ Astronomisches Institut der Universität Würzburg, Am Hubland, D-97074 Würzburg, Germany

-received date- ; -accepted date-

Abstract. We have observed an outburst of the T Tauri star EX Lup in March 1994. We present both photometric (BVR) and spectroscopic (low and medium resolution) observations carried out during the decline after outburst. The star appears much bluer during outburst due to an increased emission of a hot continuum. This is accompanied by a strong increase of the veiling of photospheric lines. We observe inverse P Cygni profiles of many emission lines over a large brightness range of EX Lup. We briefly discuss these features towards the model of magnetospherically supported accretion of disk material.

Key words: Stars: flare – Stars: pre-main sequence – Stars: individual: EX Lup

1. Introduction

The variability of EX Lup was discovered by Miss E. Janssen in 1944 while examining spectral plates at the Harvard Observatory (McLaughlin 1946). Herbig (1950) first pointed out the similarity of EX Lupi's spectral characteristics and T Tauri stars with strong emission lines of H, CaII, FeII, and HeI. In one of the spectrograms he obtained in 1949/1950 the H and CaII lines clearly show an inverse P Cygni profile. Herbig (1977a) assigned the spectral type of M0:eV using the 5850-6700 Å range. Photographic and visual light-curves covering a century of observations revealed the irregular photometric behaviour of the star (McLaughlin 1946, Bateson et al. 1990). Outbursts of up to 5 magnitudes may occur, but the star normally shows only small amplitude irregular variations. The most prominent events last about one year. The typical recurrence time scale of outbursts is of the order of a decade.

Up to now there are only a few other stars known with comparable outburst characteristics (Herbig 1989). This small group of very active T Tauri stars has been called EXors or sometimes sub-FUors. Both names point to an affinity to the so called FU Orionis stars (FUors). FUors are another group of young low mass stars with even stronger outbursts lasting for decades. Unlike EXors, during an outburst FUor spectra turn from T Tauri characteristics to that of much earlier F or G supergiants lacking strong line emission (Herbig 1977b). FUors have high

mass accretion rates ($\dot{M}_{acc} \geq 10^{-4} M_{\odot} yr^{-1}$, Hartmann 1991) and strong winds (e.g. Calvet et al. 1993) and they may be the source that drive Herbig-Haro flows (Reipurth 1989).

EXors are little studied, but potentially of great interest because they may represent an intermediate level of activity between ordinary active T Tauri stars and full blown FU Orionis eruptions. In order to cast further light on this interpretation, we have followed some EXors spectroscopically and photometrically during 1993 and 1994.

2. Observations

The star EX Lup has been at a low level of activity during the 1980's. In the early 1990's this situation changed and the star became active (Jones et al. 1993, Hughes et al. 1994). Amateur observations (Variable Star Section of the Royal Astronomical Society of New Zealand, unpublished) indicated a strong brightening in February/March 1994. Patten (1994) reports some follow-up photometric and low resolution spectroscopic observations of the same outburst.

In this paper we present part of our optical observations of EX Lup taken at ESO, La Silla. We concentrate on data obtained during the outburst in March 1994 and include some spectroscopic observations carried out in August 1994 when the star only exhibited post-outburst low level activity. A complete presentation of our data will appear in a future paper.

3. Photometric results

Differential CCD photometry has been carried out at the 0.9m-Dutch and the 1.54m-Danish telescopes. This photometry was later calibrated with respect to standard stars including extinction and colour corrections. All reductions have been made with the APPHOT package in IRAF. Typical errors (1σ) in the differential photometry are $\Delta B=0.005$, $\Delta V=0.004$, $\Delta R=0.004$ whereas the absolute magnitude scale itself is accurate to about 0.01 in all three colours.

The resulting lightcurves in B, V, and R are presented in Fig. 1. The maximum occurred between February 25 and March 4 (Herbig, priv. comm.). The fading tail of the eruption can be described as an exponential decline with small fluctuations superimposed. Variability of more than 0.1mag is present on timescales of less than one hour (e.g. March 6.3, see also Patten 1994). Figure 2 displays the colour change in B-V during the decline. The star clearly becomes redder when fading. For

Send offprint requests to: Thomas Lehmann, e-mail: lehmi@sol.astro.uni-jena.de

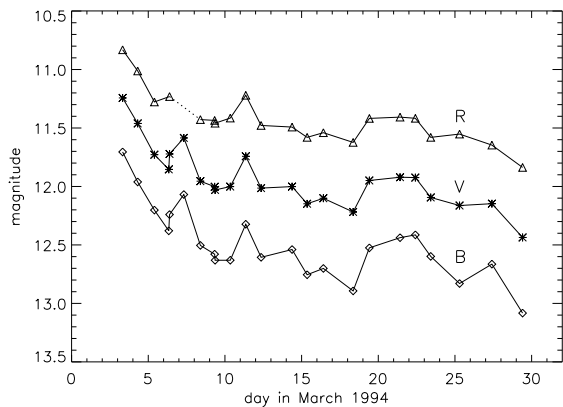


Fig. 1. Photometry obtained in March 1994. R (*top*), V (*middle*) and B (*bottom*) lightcurves.

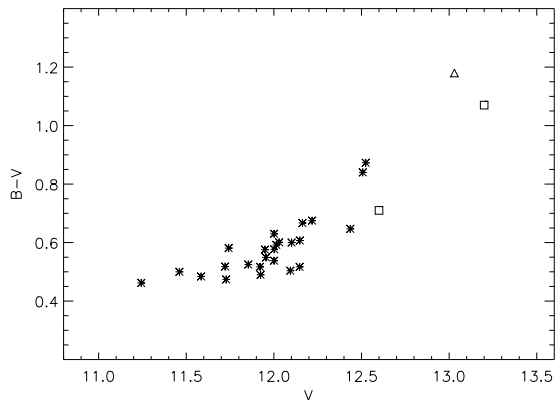


Fig. 2. V - (B-V) magnitude-colour diagram. A few measurements were taken from literature: Herbig et al.1992 (*squares*), Bastian & Mundt 1979 (*triangle*).

comparison we have included some points close to minimum light taken from the literature. The outburst amplitude was about $\Delta V=2.0\text{mag}$ and $\Delta B=2.6\text{mag}$.

4. Spectroscopic results

Spectroscopic observations in the blue spectral range were carried out during the first few nights in March 1994 on the ESO-1.52m telescope using the Boller & Chivens spectrograph at 1.2\AA resolution. After the decline of EX Lup we obtained post-outburst spectra in the same wavelength region at resolutions of 1.5\AA and 12\AA at the 3.5m-NTT with EMMI in August 1994. All spectra have been reduced with the CTIOSLIT package in IRAF. Observations of spectrophotometric standards and nightly extinction curves allowed for a flux calibration.

In Fig.3 we present two spectra of EX Lup: one close to the outburst maximum and the other at low activity almost half a year after the eruption. Some of the emission lines of H, CaII, FeII, HeI, and HeII are indicated. Under the assumption that the total light can be decomposed into an underlying T Tauri star photosphere, a continuum source, and superimposed emis-

sion lines, we now discuss the different spectral components and their variability.

4.1. Continuum emission

A powerful method to determine the continuum excess emission is to determine the veiling by comparison with spectra of stars of the same spectral type and luminosity class but lacking any disk signature (Hartigan et al. 1989, 1991). The accuracy of the veiling determination decreases rapidly when the emission component exceeds the photospheric luminosity. In the case of EX Lup during its eruption we therefore did not intend to derive the veiling and the true excess emission spectrum by comparison with spectral type standards, but we could examine the spectral variability caused by the outburst.

No photospheric absorption features are seen during the outburst (upper spectrum in Fig.3) but they appear in the post-outburst spectrum. Thus the major source of variability presumably is a featureless continuum. Therefore, a difference spectrum between outburst and post-outburst spectra should be a good measure of the continuum emission spectrum. In Fig. 4 we plot two difference spectra at low resolution. The first shows the difference between an outburst (March 3) and a post-outburst (August 16) spectrum, while the second shows the difference between two post-outburst (August 18 and 16) spectra which displays normal low-level variability. The continuum emission spectrum displaying the normal low-level activity is bluer than the continuum emission present during outburst.

4.2. Emission lines

The most intriguing features in the spectra of EX Lup are strong emission lines. The Balmer series can be seen up to H15 especially during times of minimum activity. Equivalent widths and fluxes of individual lines are given in Table 1. Essentially all strong emission lines have increasing fluxes as the star brightens. However due to the steep rise of the continuum the equivalent widths decrease, which is also evident in the data from Patten (1994) at $H\alpha$, $H\beta$, and $H\gamma$ during the maximum. Obviously the CaII lines have a larger flux amplification during the outburst than the Balmer lines. There is some indication that line fluxes of metals do not increase while the star goes into outburst (CaI, FeII, SrII).

The presence of inverse P Cygni profiles in the strongest emission lines during outburst, as first noted by Herbig (1950), is here corroborated. At Balmer lines higher than H9 the equivalent width of the redshifted absorption dip is even larger than the width of the emission component. Comparing the sequence of spectra between March 3 and 6 we can see a substantial fading of the absorption. The mean velocity displacement of the absorption measured in these spectra is $+240 \pm 20$ km/s. This absorption component is still visible in our spectrum taken on August 18 (Fig.5a). We also plot the difference between the two spectra from August 18 and August 16 to enhance the visibility of the absorption dip and to remove possible contamination due to photospheric lines. The displacement of the absorption dip measured in the post-outburst difference spectrum corresponds to a velocity of $+360 \pm 20$ km/s.

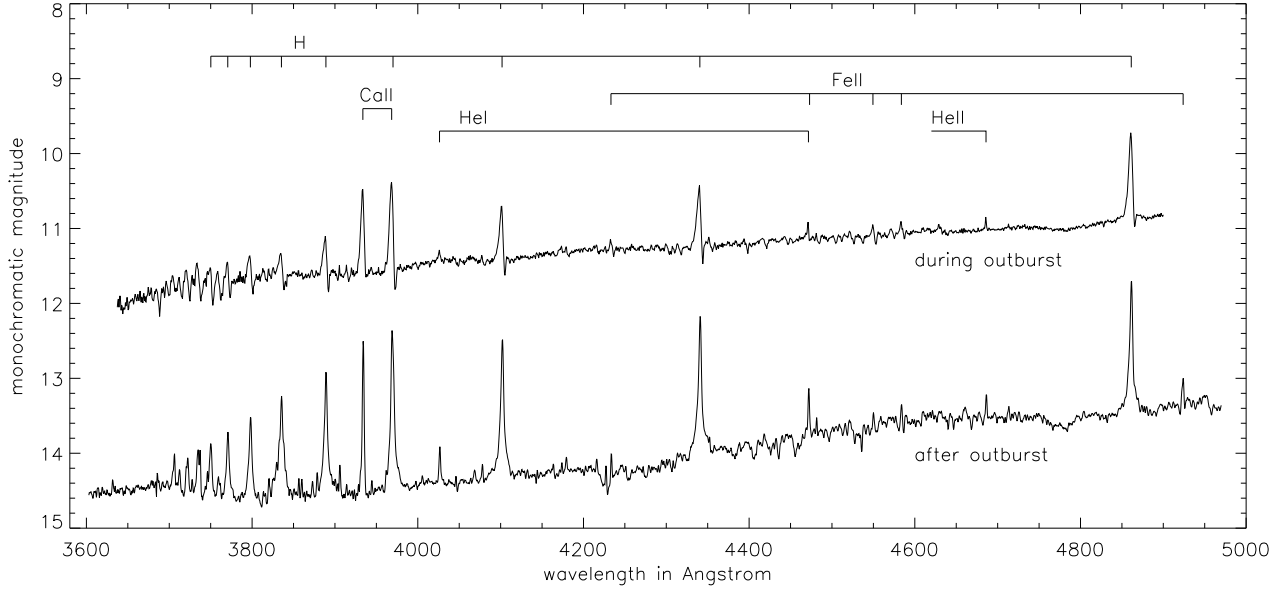


Fig. 3. Medium resolution spectra of EX Lup. Fluxes are expressed in magnitudes according $\text{mag} = -2.5 \log (F_{\nu}/F_0)$ where F_{ν} is the flux per unit frequency and $F_0 = 3.68 \times 10^{-20} \text{ erg/cm}^2/\text{s/hz}$. Some emission lines of H, CaII, FeII, HeI, and HeII are indicated. Inverse P Cygni profiles in the strongest emission lines are visible in the outburst spectrum from March 3 (*top*). Photospheric absorption features (e.g. CaI 4227) appear in the post-outburst spectrum from August 16 (*bottom*).

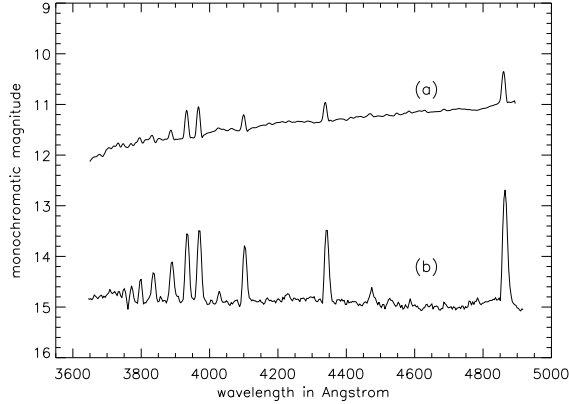


Fig. 4. Excess emission - Comparison of outburst and low level variability at low spectral resolution. These spectra are a good approximation to the excess emission spectra which are superposed on the stellar photospheric spectrum. (a) The outburst as given by the difference of the spectra from March 3 and August 16. (b) Post-outburst variability derived from spectra from August 18 minus August 16. Note the Balmer jump emission and the bluer continuum.

Table 1. Comparison of selected emission lines at different levels of activity. Equivalent widths and line fluxes during the outburst measured on March 3 (^{high}) and in the post-outburst spectrum on August 16 (^{low})

Identification	$W_{\lambda}^{\text{high}}$ Å	W_{λ}^{low} Å	$\text{flux}^{\text{high}}$ $\frac{10^{-14} \text{ erg}}{\text{cm}^2 \text{ s Å}}$	flux^{low} $\frac{10^{-14} \text{ erg}}{\text{cm}^2 \text{ s Å}}$
H11 3771	-1.0	-4.2	16	6
H10 3798	-1.5	-7.0	25	9
H 9 3835	-1.2	-12.1	20	16
H 8 3889	-2.7	-13.0	44	18
SiI 3906	-0.2	-0.8	3	1
CaII 3934	-7.7	-12.0	123	15
CaII 3968	}	-8.8	145	27
He3970				
HeI 4026	-0.4	-1.3	7	2
Hδ 4102	-4.5	-20.5	79	25
SrII 4216	-0.2	-0.4	3	5
CaI 4227	-0.1	-0.7	2	7
FeII 4233	-0.4	-0.7	7	8
Hγ 4340	-5.9	-20.2	107	29
HeI 4472	}	-0.4	8	3
FeII 4473				
HeII 4686	-0.3	-0.9	6	2
Hβ 4861	-9.4	-16.8	196	30
FeII 4924	—	-1.5	—	2

4.3. Photospheric absorption features

Photospheric features of the underlying T Tauri star can be seen only in the post-outburst spectra. Figure 6 shows the region around CaI 4227, which is the strongest stellar absorption line, in two post-outburst spectra. The difference of these two spectra no longer exhibits the absorption line, and the change of total flux by about 40% is therefore due to continuum emission rather than photospheric variability.

The photospheric lines of the T Tauri star are veiled, even at minimum brightness. The superimposed emission line spectrum additionally fills in many absorption lines. The measurement of the veiling is therefore rather difficult. We find a good fit to the observed strength of absorption lines by introducing a flat continuum emission equal to the photospheric con-

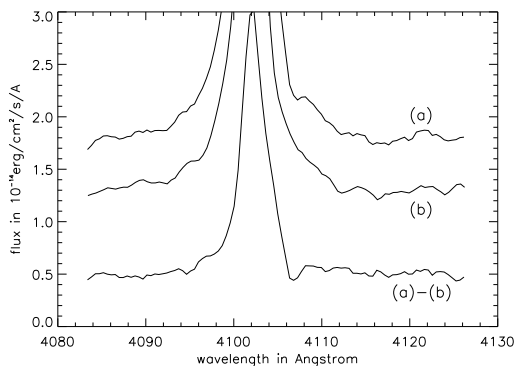


Fig. 5. Visibility of inverse P Cygni profiles in medium resolution post-outburst spectra at H δ . (a) spectrum 18.08.94 (b) spectrum 16.08.94 (a)–(b) post-outburst variability (difference spectrum), the redshifted absorption dip of the H δ line indicating an infall velocity of about 360 km/s is clearly visible

tinuum of the underlying star (veiling $r=1$, comparison with HD 202560, spectral type M0V) at 4200 Å when the brightness of EX Lup is $V=13.0$.

5. Discussion and conclusions

The outburst of EX Lup can be understood in terms of a mass accretion event causing increased continuum emission in a hot region close to the surface of the star where the infalling matter finally releases its kinetic energy. The total light of the photosphere and the hot region becomes dominated by the latter and therefore it is much bluer during the outburst. Furthermore all photospheric lines are heavily veiled (assuming that $r=1$ at minimum light then the veiling during outburst would be $r \approx 20$). The different slope of the continuum emission in the outburst compared to the post-outburst (see Fig.4) indicates that the hot region is *cooler* during outburst (assuming no change in extinction due to circumstellar matter). This interpretation then implies a dramatic expansion of the hot region in order to account for the observed rise in luminosity during the outburst.

The inverse P Cygni profiles of many emission lines prove the infall motion of accreted material. The velocity derived from the redward displacement of the absorption component of these lines are of the order of 300 km/s and therefore much higher than those assumed in the classical boundary layer model for T Tauri stars (Lynden-Bell & Pringle, 1974). However, these high infall velocities may result from magnetospherically mediated disk accretion (Camenzind 1990, Königl 1991, Hartmann et al. 1994). High resolution studies of classical T Tauri stars have revealed a large fraction of stars exhibiting inverse P Cygni structures (e.g. Appenzeller 1977, Edwards et al., 1994). The usual low level variability might be caused by geometrical effects during the rotation of the star. The more dramatic outbursts could be attributed to episodic changes in the magnetosphere, resulting in more extended infall flows of circumstellar material onto the star.

Acknowledgements: We thank G.Herbig for alerting us to the outburst of EX Lup in early March 1994. Also we are grateful to the following observers for kindly providing part of their ob-

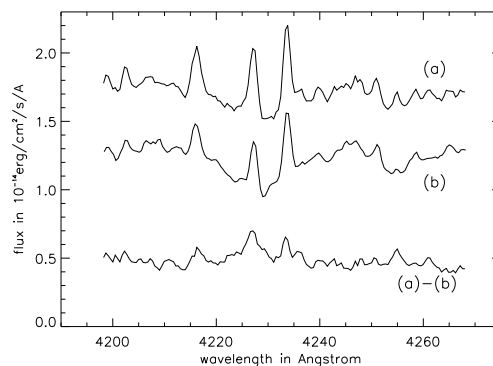


Fig. 6. Photospheric absorption lines in medium resolution post-outburst spectra around CaI 4227. Note also the presence of narrow emission lines SrII 4216, CaI 4227, FeII 4233. (a) spectrum 18.08.94 (b) spectrum 16.08.94 (a)–(b) post-outburst variability (difference spectrum), photospheric absorption disappears

serving time: T.Abbott, J.F.Claeskens, D.De Winter, C.Flynn, H.Jerjen, A.Machado, F.Patat, N.Robichon, P.Stein. TL & WB were supported by student fellowships of the European Southern Observatory. WB acknowledges support by the Deutsche Forschungsgemeinschaft (DFG) under grant Yo 5/16-1.

References

- Appenzeller I., 1977, *A&A* **61**, 21
- Bastian U., & Mundt R., 1979, *A&AS* **36**, 57
- Bateson F.M., McIntosh R., & Brunt D., 1990, *Publ. of Var.Star Section of the Roy.Astron.Soc. of New Zealand* No.16, 49
- Calvet N., Hartmann L., & Kenyon S.J., 1993, *ApJ* **402**, 623
- Camenzind M., 1990, *Rev. Mod. Astron.* **3**, 234
- Edwards S., Hartigan P., Ghandour L., & Andrulis C., 1994, *AJ* **108**, 1056
- Hartigan P., Hartmann L., Kenyon S., & Hewett R., 1989, *ApJS* **70**, 899
- Hartigan P., Kenyon S.J., Hartmann L. et al., 1991, *ApJ* **382**, 617
- Hartmann L., 1991, in *The Physics of Star formation and Early Stellar Evolution*, ed. C.J. Lada & N.D. Kylafis, Kluwer Academic Publishers, p.623
- Hartmann L., Hewett R., & Calvet N., 1994, *ApJ* **426**, 669
- Herbig G.H., 1950, *PASP* **62**, 211
- Herbig G.H., 1977a, *ApJ* **214**, 747
- Herbig G.H., 1977b, *ApJ* **217**, 693
- Herbig G.H., 1989, in *Low Mass Star Formation and Pre-Main Sequence Objects*, ed. B. Reipurth, ESO Conference and Workshop Proceedings No.33, p.233
- Herbig G.H., Gilmore A.C., & Suntzeff N., 1992, *IBVS* No.3808
- Hughes J., Hartigan P., Krautter J., Kelemen J., 1994, *AJ* **108**, 1071
- Jones A.F., Albrecht W.B., Gilmore A.C., & Kilmartin P.M., 1993, *IAUC* No.5791
- Königl A., 1991, *ApJ* **370**, L39
- Lynden-Bell D., & Pringle J.E., 1974, *MNRAS* **168**, 603
- McLaughlin D.B., 1946, *AJ* **52**, 109

Patten B.M., 1994, *IBVS* No.4049
Reipurth B., 1989, *Nature* **340**, 42